



Dam implications on salt-water intrusion and land use within a tropical estuarine environment of the Gulf of Mexico

J.C. Alcérreca-Huerta^a, M.E. Callejas-Jiménez^{b,*}, L. Carrillo^b, M.M. Castillo^c

^a Consejo Nacional de Ciencia y Tecnología-El Colegio de la Frontera Sur (CONACYT-ECOSUR), Department of Systematics and Aquatic Ecology, ECOSUR, Av. del Centenario km 5.5, Chetumal, Mexico

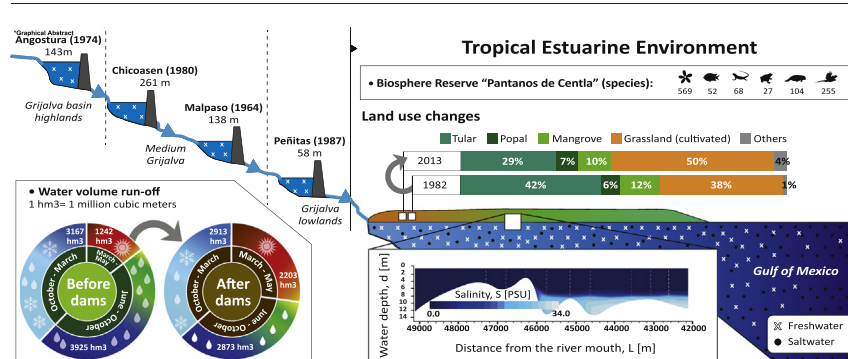
^b Department of Systematics and Aquatic Ecology, El Colegio de la Frontera Sur, Av. del Centenario km 5.5, Chetumal, Mexico

^c Department of Sustainability Sciences, El Colegio de la Frontera Sur, Carretera Villahermosa-Reforma km 15.5, Ranchería Guineo, sección II, Villahermosa, Mexico

HIGHLIGHTS

- An upper-estuary in Southern Gulf of Mexico is analyzed through field measurements.
- Characterization of the current seasonal dependency of the salt-wedge is provided.
- Dam implications on salt-wedge and land use changes are identified.
- Loss on hydrological seasonality is the major direct impact to the upper-estuary.
- System-stress is induced by cultivated grasslands despite conservation policies.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:

Received 11 May 2018

Received in revised form 16 October 2018

Accepted 21 October 2018

Available online 22 October 2018

Editor: Ralf Ludwig

Keywords:

Water management

Salt-wedge

Dam impacts

Land use

Vegetation cover

Tropical estuary

ABSTRACT

Estuaries are highly productive ecosystems, defined by salt-freshwater exchanges that are significantly altered by changes upstream and in adjacent coastal areas. Tropical estuaries are characterized by the periodic advance and retreat of saline intrusion, depending on seasonality, episodic river flows and flooding events. Salt-water intrusion due to the estuarine dynamics might be affected by dam systems, which could modify the hydrological regime of the estuary in relation to other stressors, such as land use changes. For this purpose, field measurements of salinity, temperature, river-discharge and flow velocities were conducted over a year to analyze the current hydrological regime in the upper estuary of the Grijalva River in the southern Gulf of Mexico, part of the Biosphere Reserve “Pantanos de Centla”, one of the most biodiverse areas in the world. Analysis of land use and vegetation cover was performed. Historical implications of the hydrological performance of the four-dam system (1957 to 2014) are presented, together with the upstream-induced changes (i.e. discharge and seasonal water volumes variations): before, between and after the full operation of the dam system. A general loss of seasonality in the river discharge was identified (1974–1987), when critical mean annual water discharges were registered (Q_{mean} from 263.56 to 126.49 m³/s). Chronological changes in the estuary and in the surrounding area due to the introduction of large extensions of cultivated grassland (~1020 km²), reduction in mangrove cover (~223 km²) and tular (~1340 km²) were noticed. These modifications mostly occurred before conservation strategies were implemented, such as the designation of the Biosphere Reserve (1992). This study contributes to a better understanding of the response of estuarine systems to anthropic perturbations and the development of long-term management plans that could take into account climate change and the increase of hydropower development.

© 2018 Elsevier B.V. All rights reserved.

* Corresponding author.

E-mail address: mecallejas@ecosur.mx (M.E. Callejas-Jiménez).

1. Introduction

Estuaries are among the most productive ecosystems in the world because of their high-biological productivity due to nutrient transport, serving as feeding, breeding and protective habitats for numerous organisms (Savenije, 2012; Wolanski and Elliott, 2016). The estuarine environment is characterized by a constantly fluctuating mixture of salt, and freshwater which are greatly influenced by changes upriver and in adjacent coastal areas (McLusky and Elliott, 2004). Estuary and river dynamics have been altered worldwide as a consequence of the cumulative impacts of human activities, driven by economic gain or the safety to meet water, energy and transportation needs (Nilsson et al., 2005). Infrastructure for flood protection, dredging and maintenance of navigation channels, land use changes for agriculture, livestock and aquaculture are among the human interventions which alter estuarine dynamics and are superimposed on the effects of climate change (Bates et al., 2008; Wang et al., 2015) and sea level rise (Chua and Xu, 2014; Prandle and Lane, 2015; Yang et al., 2015).

Although estuaries have unifying features and are subject to similar stress factors, the dynamics and response of tropical estuaries differ significantly from temperate estuaries. The variability and timing of major physical forces in tropical conditions are highly dependent on episodic river flow conditions and insolation rates (Eyre and Balls, 1999). The dynamic salinity structure in tropical estuaries has also been shown to be dominated by flood events (Eyre and Balls, 1999) induced by variable rainfall and run-off episodes, with periodic advances and retreats of the salt intrusion, depending on a less pronounced seasonality (2–3 seasons) and lower tidal variations (Gong and Shen, 2011; Shivaprasad et al., 2013).

The estuarine environment may also present salt-wedges when the tidal range is microtidal and the river discharge is sufficient to induce stratification, i.e. when a balance of inertial and frictional forces with the baroclinic pressure gradient keeps the interfacial structure between salt- and freshwater under a quasi-steady form (Geyer and Farmer, 1989). Several studies have been developed focused on estuary flows and salt-wedges by considering salt intrusion, mixing or stratification (e.g. Anh Duc, 2008; Bricheno et al., 2016; Gong et al., 2012, 2013), but they are limited to the physics behind these processes without considering the interaction with land use changes, water management modifications and ecological implications based on field and historical data. The volume and seasonality of river discharge are primary factors to evaluate deltaic resiliency, shelf plume, and estuarine dynamics. Therefore, projecting how these parameters are affected is critical for assessing the environmental vulnerability and fragmentation of natural dispersal pathways (Feng et al., 2017; Jansson et al., 2000). Changes in the river discharge regime, due to the operation of hydropower dams, lead to an inherent regulation in catchment run-off in the rainy season and its release during dry seasons (Nilsson et al., 2005; Zarfl et al., 2015). Therefore, river discharge has a complex relationship not only with climate, but also with often conflicting terrestrial activities and processes in the watershed, which include natural as well as anthropogenic effects on land cover and plant succession (Kemp et al., 2016). Thus, studies in tropical estuaries that focus on human-induced impacts are still needed.

The interaction between internal and external drivers of change on estuaries is relevant for developing management tools and identifying patterns for their conservation. Particularly, for the tropical estuary of the Grijalva River in the southern Gulf of Mexico, dam-induced stressors in the lowlands have been recognized (INECC, 2018). The present paper thus aims to investigate the seasonality of the saltwater intrusion in the upper-estuary of the Grijalva River, within the Biosphere Reserve “Pantanos de Centla”. A brief description of the study area, the sampling techniques, and data collection are presented first. Results on salt-intrusion and characterization of the upper-estuary are provided based on monthly field measurements of physical variables. Analysis of river discharge modifications was conducted, considering the

development of the four-dam system management plan (i.e. before, during and after the dam system functioning). Anthropogenic stressors beyond the dam operation are presented in relation to land-use and land cover changes through comparison of historical records. The findings are discussed to better understand the measured condition of the estuarine system and possible threats caused by external stressors.

2. Materials and methods

2.1. Description of the study area

The Grijalva-Usumacinta system, in the south of the Gulf of Mexico, is a tri-national basin shared between Mexico, Guatemala, and Belize, of approx. 130,700 km² (García García and Kauffer Michel, 2011; López-Ramírez, 2007). It is considered the second most important delta in terms of discharge in North- and Central-America (Psuty, 1965, 1967).

The study area is part of the lowlands of the Grijalva-Usumacinta basin within the Biosphere Reserve of “Pantanos de Centla” (BRPC) (Fig. 1). It has been protected since 1992 by the Mexican government, included in the List of Wetlands of International Importance in 1995 and declared as Reserve by UNESCO in 2006, due to its biodiversity and safeguarding of a large number of species of flora (569), fish (52), reptiles (68), amphibians (27), mammals (104) and birds (255) (RAMSAR, 2001; SEMARNAT, 2016; UNESCO, 2012). The BRPC represents approx. 23% of the flora and fauna species (~4250) reported for the state of Tabasco, where 53% of the freshwater wetlands of Mexico are found (Barba-Macías et al., 2006; Sánchez and Barba-Macías, 2005). It has also been considered among the 15 largest wetlands in the Americas and one of the most important in Mesoamerica with estuaries, marshes, swamps and mangrove areas (RAMSAR, 2001; SEMARNAT, 2016). Also, next to the BRPC, the Protected Area of Fauna and Flora “Laguna de Términos” (APFFLT) created in 1994 is found. These two areas comprise a very complex hydrological system with important hydrological connections, as shown in Fig. 1. The plain of the Grijalva River estuary, due to its low relief with respect to sea level, is highly vulnerable to hydrometeorological (Kauffer Michel, 2010; Rodríguez, 2010) and marine phenomena (Ortiz-Pérez, 1992).

The warm-humid climate in the area is characterized by an average annual temperature of over 22 °C, with rainy (June–October) and dry (March–May) seasons, an average precipitation of 4500 and 200 mm, respectively. Winter rainfall, associated with the cold fronts or “Nortes” that prevail from October to March, provide an average precipitation of 1200 mm. The most important rivers in the basin and in the Reserve have an annual medium superficial discharge to the Gulf of Mexico of approx. 101 Mm³ of water (CONAGUA, 2016). The Grijalva River begins in Guatemala. In Mexico, after passing a four-dam system (i.e. “La Angostura”, “Chicoasén”, “Malpaso” and “Peñitas” dams), the river is known as the Mezcalapa and Carrizal, then its name changes back to the Grijalva beyond the tributary of the Sierra River. The Grijalva River passes through the City of Villahermosa (with about 857,000 inhabitants), before connecting with branches of the Usumacinta River to finally discharge in the southern Gulf of Mexico (Fig. 1). Microtidal conditions at the river mouth are predominantly diurnal with a tidal range of 0.65 and 0.15 m during spring and neap tides, respectively (Medellín et al., 2013). The floodplains in this area are also relevant by providing positive effects on the water cycle, flow regulation and maintenance of the water quality for the habitats of the BRPC, the APFFLT and those of the surrounding unprotected areas (Laino-Guanes et al., 2016).

Multiple and complex system interactions are present in the area as environmental and land use conflicts due to human activities occur with negative consequences on water quality and ecological status of riverine ecosystems (Valle Junior et al., 2014a, b, 2015). Before the dams, there were already impacts and alterations in the system, related to prehispanic agrosystems and water management plans (prior to the 16th century), which became emergent tropical plantations and felling areas (18th and 19th centuries) (Tudela, 1992). Furthermore, during

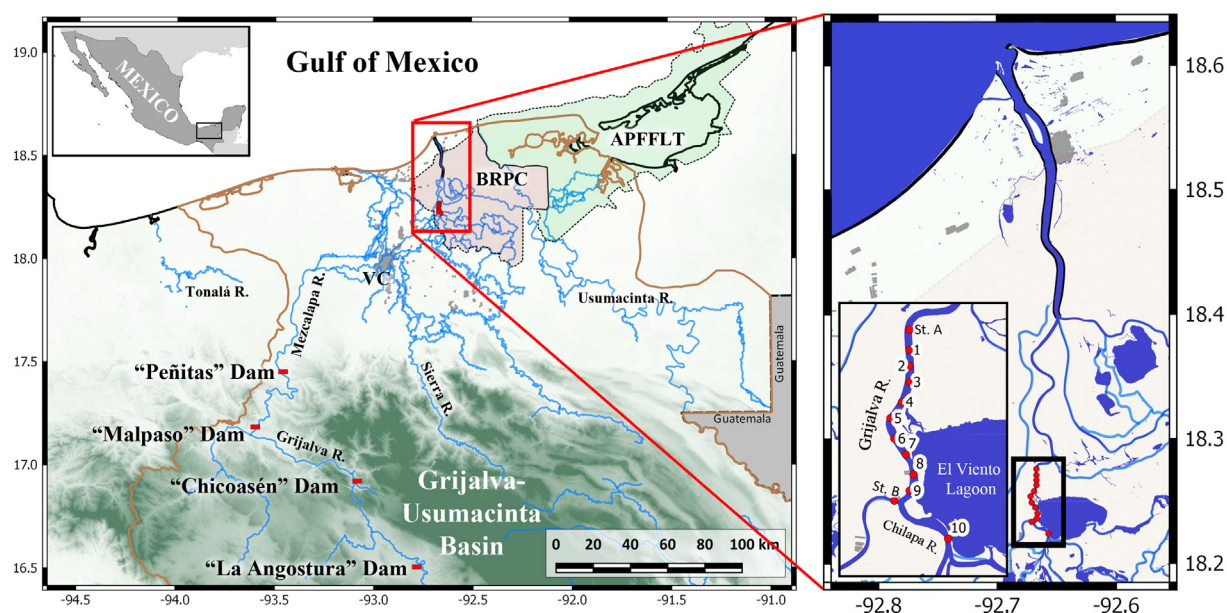


Fig. 1. Study area showing the location of the four-dam system, Villahermosa City (VC) and protected natural areas (left panel): Biosphere Reserve of "Pantanos de Centla" (BRPC) and Protected Area of Fauna and Flora "Laguna de Términos" (APFFLT). Numbers represent the location in which measurements were conducted (right panel).

the first half of the 20th century, the policies enacted in the lowlands of the Grijalva River were based on an intensive agricultural development, animal husbandry and the exploitation of oil fields in the area. Four dams were constructed on the Grijalva River (1959–1987) (Fig. 1 and Table 1) as part of an important program for the regulation of floods, drainage of the coastal plains and lowlands of the Basin for the agricultural and animal husbandry exploitation, the integration with national water management plans, development of human settlements and hydropower generation (Tudela, 1992). The energy provided by the dam system is currently about 4800 MW (effective capacity), which in 2015 represented 38.6% of the total hydropower capacity in operation in Mexico (World Energy Council, 2016) and 8.5% of the total energy generated in the country (CFE, 2016).

2.2. Sampling techniques and data analysis

Prospective assessment of the study area for identification of the upstream limit of the salt-intrusion was conducted in June and July 2016. Monthly measurements were taken along a segment of the upper-estuary of the Grijalva River from August 2016 to June 2017. Vertical profiles of salinity and temperature were obtained by means of a CTD profiler YSI CastAway. Velocity measurements were made with a RiverPro ADCP (Acoustic Doppler Current Profiler) 1200 kHz RD Instruments (fully integrated GPS for geo-referencing) in order to obtain the river discharge as well as detailed cross-sectional velocity fields. Fixed stations (St.) were selected to detect the presence of the salt-wedge during the annual cycle, one located 42.1 km upstream of the river mouth (St. A) and the other (St. B) about 5.2 km upstream from St. A on the Grijalva River, close to its intersection with the Chilapa River

tributary and their connection with El Viento Lagoon (Fig. 1). These stations (St. A and St. B) were set on the Grijalva River, directly related to a previous water quality monitoring of May 2016, and the prospective measurements.

During the dry season (5th June 2017) CTD casts along the river were conducted to accurately represent the salt-wedge structure along the river. Considering St. A as a reference point, the CTD measurements were uniformly distributed every ~500 m upstream (St. 1–9) towards St. B (Fig. 1) and with St. 10 related to the features induced by the tributary. The river depth profile was obtained in order to account for morphological elements that may restrict the salt-wedge intrusion.

Historical records on river discharge from 1957 to 2014 (CONAGUA, 2018) at the González hydrometric station (17.9750°N, 93.0000°W, about 84 km from the study site at the Grijalva River) were analyzed. These results allow the identification of possible implications of the dam construction on the development of the current salt-wedge. The daily discharge records were averaged for the years within the following periods: i) before the operation of the first dam (1957–1964); ii) after the starting operation date of the first (1964–1974), second (1974–1980), and third dam (1980–1987), as well as iii) after the four-dam system began full operation (1987–2014). The analysis of seasonal run-off water volumes was made for the rainy (16th June–15th October), dry (1st March–15th June) and Nortes seasons (16th October–28th February), considering a daily integration of the averaged hydrographs per period (i, ii, iii).

Land use and vegetation cover registries from 1982, 1997, 2003 and 2013 by INEGI (2018) for the area (18.00–18.60°N and 92.00–94.00°W) were also considered to identify changes in recent decades in the estuary that could be related to the extension of the salt-wedge length and the reduction in catchment run-off. The techniques used for the development of the registries were based on the interpretation of aerial photogrammetry (for 1982) and the application of photo-interpretation techniques of LANDSAT TM & ETM+ satellite imagery (for 1997, 2003 and 2013) (Franco Maass et al., 2006).

3. Results

3.1. Upper-estuarine salt wedge characterization

From the field measurements at stations A and B, the temperature and salinity profiles are observed as a function of time along an annual

Table 1

Features of dams within the hydropower system upstream the study area. Source: (CONAGUA, 2018, 2016).

Dam	Year of construction	Dam height [m]	Water reservoir [hm ³]	Effective capacity [MW]
"La Angostura"	1969–1974	143	13,169.00	900
"Chicoasén"	1974–1980	261	1384.86	2400
"Malpaso"	1959–1964	138	12,373.10	1080
"Peñitas"	1979–1987	58	1091.10	420
Total			28,018.06	4800

cycle (Fig. 1). The results show the initial freshwater conditions of the water column, the salt-intrusion at the beginning of the dry season and the subsequent stratification for the development of the salt-wedge.

The water column changed from a fully freshwater condition to a stratified one (January 31st to March 6th), in which the salt-intrusion is clearly seen (Fig. 2a and b). Mixing between the incoming salt-front and the river discharge is particularly noticeable in March, resulting in non-stratified profiles. In the dry season (March to June), the salt-intrusion is clearly observed at St. A with salinities of 2–28 PSU (Fig. 2a). The maximum salinity at this station reached 32.57 PSU (June 5th) with a very well-defined halocline at 8.257 m depth, a value that remained similar to that observed in May. It is worth mentioning that for St. B, the saline intrusion was only observed with salinity values <12.0 PSU in March and not present in the rest of the dry season, even though higher salinity values were observed in St. A. Also, the temperature at both stations (Fig. 2a and b) shows the greater seasonal variation: 25.0 °C (January) and up to 30–31 °C (March–June and September). During April, differences of 3.5–4.0 °C were identified between the upper and bottom river layers at St. A, with the thermocline at water depth 8.468 m. However, smaller differences of 1.0–1.5 °C were normally observed in the water column during the dry season. Similarly, homogenous temperature profiles were observed at St. A and St. B in the rainy season.

In addition to the salinity and temperature variations, changes in the bottom depth occurred at St. B (Fig. 2), varying from 13.88 to 5.23 m, with multiple fluctuations throughout the year. Such changes in bottom depth were not observed at St. A.

The monthly variation of river discharge (Q_{AV}) and the changes of depth-averaged temperature (T_{AV}) and salinity (S_{AV}) at St. A were analyzed (Fig. 3a). The surface to bottom differences for salinity ($\Delta S = S_{bottom} - S_{surface}$) and temperature ($\Delta T = T_{bottom} - T_{surface}$) was also estimated as a proxy to stratification (Fig. 3b). The river discharge remained with a value around 518 m³/s (January to July), while an increase on T_{AV} and ΔS was observed (Fig. 3). The maximum ΔS occurred in June (32.57 PSU), just before the rainy season, despite the maximum S_{AV} occurring in March (17.06 PSU). In this regard, the salinity

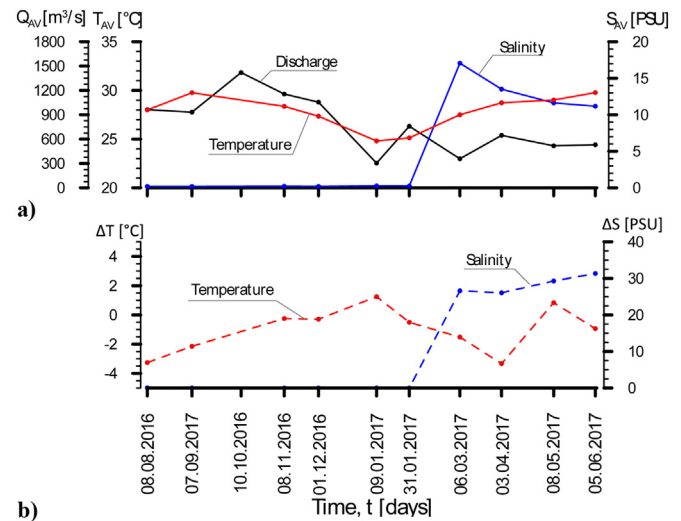


Fig. 3. Monthly measurements at St. A for: a) depth-averaged discharge (Q_{AV}), temperature (T_{AV}) and salinity (S_{AV}) and b) surface to bottom differences for temperature (ΔT) and salinity (ΔS).

stratification (ΔS) increased with temperature (T_{AV}) but the river discharge (Q_{AV}) fell.

Low temperatures associated with high salinity as a function of water depth for the upper estuary of the Grijalva River are shown in the Temperature-Salinity (T-S) diagram (Fig. 4). The salt-wedge in the Grijalva estuary featured temperatures of 28.61–29.59 °C, salinity higher than 20 PSU and up to 32.724 PSU, and water densities $\rho > 1010$ kg/m³, mainly at water depths $d > 8.3$ m. The transition between salt- and freshwater was observed for water depths around 5.6 and 8.3 m, temperatures of 29.44–30.40 °C, wide salinity fluctuations of 1.0–20.0 PSU and water densities $993 < \rho < 1010$ kg/m³. The freshwater in the estuary, coming from the Grijalva River, was characterized by its salinity (<1.0 PSU), water density ($\rho \approx 992$ kg/m³) and water depths up to 5.6 m, with its temperature varying from 29.03–30.41 °C.

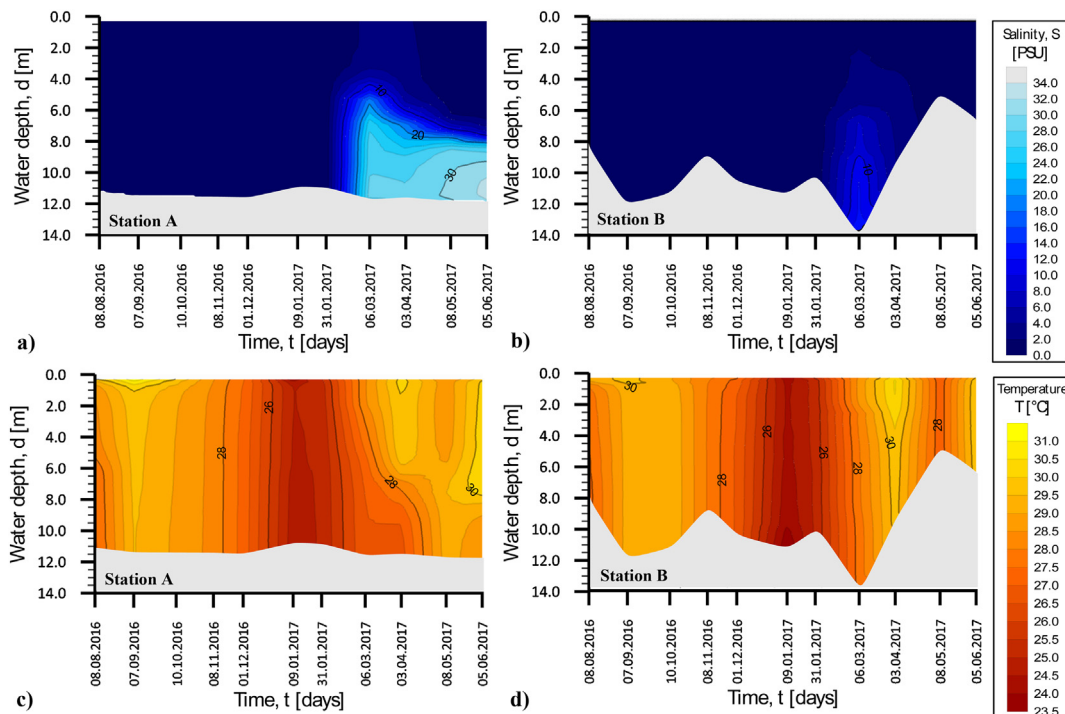


Fig. 2. Vertical salinity (PSU) and temperature (°C) profiles during an annual cycle at Station A (a, c) and Station B (b, d).

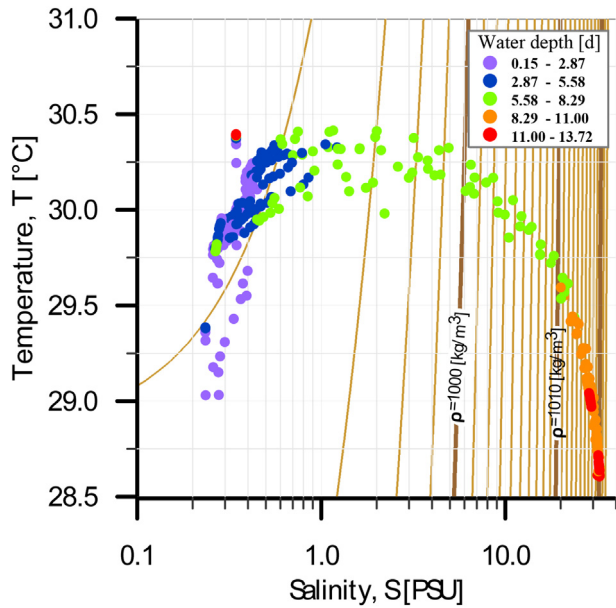


Fig. 4. T-S diagram as a function of water depth of the upper-estuary of the Grijalva River considering vertical profiles measured at St. A, St. B and St. 1–10 on June 5th, 2017.

The pycnocline is clearly depicted around a water depth of 8.257 m, but the intrusion of the salt-wedge upstream of the river channel seems to be obstructed by a morphological change at St. 8 (Fig. 5). This change represents a barrier that allows the presence of an ecosystem subject to seasonal salt-intrusion condition (downstream St. 8) and other where only freshwater conditions are present (upstream St. 8). The connection of the Grijalva river inflow provides a greater influence on the temperature profile downstream, but also limits the temperature-front of the Chilapa River. Therefore, while the morphology allows the definition of two subsystems as a function of the salinity (upstream and downstream St. 9), the temperature profile shows three subsystems in the estuary: i) the Chilapa River tributary, ii) the upstream Grijalva River and iii) the estuary, downstream of St. B, where the change of the profile from stratified to homogeneous occurs.

The maximum length of the estuary according to Fig. 5 rises to 46 km from the river mouth and might extend upstream. However, this extent was limited by a physical barrier between the environments, possibly

induced by sediment accumulation from the interaction between the salt-wedge and the freshwater discharge from the Grijalva and Chilapa rivers.

The intrusion of the salt-wedge at St. A was further examined by considering the velocities developed on the river cross-section (Fig. 6). The motion of the salt-wedge upstream is clearly defined below the halocline location at a depth of 8.257 m, with an average velocity magnitude of $U = 1.445$ cm/s, about 7.01% of the average velocity of the downstream flow.

3.2. Historical river discharge modifications

Fig. 7 shows the averaged-annual hydrographs (discharge vs. time). The ratio of seasonal water volume $RSWV = V_{SEASON}/V_{DRY}$ (with V_{SEASON} , as the volume during a season compared to that during dry season V_{DRY}), was estimated to account for the variation of the seasonal average water volumes at different periods. Values of RSWV closer to 1.0 indicate a decrease in seasonality.

A comparison before and after the dam system functioning clearly shows flow alteration in the Grijalva River (Fig. 7 and Table 2):

- i) Before dams (1957–1964), the seasonality of the river discharge is well-defined, reaching a maximum of $Q_{max} = 619.80$ m³/s during the rainy season and minimum of $Q_{min} = 98.71$ m³/s during the dry season, with an annual average discharge of $Q_{mean} = 263.56$ m³/s. The ratio of seasonal water volume between the rainy and dry seasons ($RSWV_1 = V_{RAINY}/V_{DRY}$) was of 3.16; i.e. the seasonal water volume for the rainy season (3925.55 hm³) was 3.16 times more than during the dry season (1241.71 hm³) (Table 2). The ratio between Nortes and dry season ($RSWV_2 = V_{NORTES}/V_{DRY}$) was of 2.55, showing the seasonality dependency of water volume run-off.
- ii) After operations began for the first dam (1964) and before that of the second (1974), an overall reduction in water run-off is noticed, with an annual average discharge from $Q_{mean} = 263.56$ m³/s to 207.15 m³/s; i.e., about 21.4% below the average in the previous period. However, a well-defined seasonality of the river discharge was still observed during this period with a $Q_{max} = 545.38$ and $Q_{min} = 63.92$ m³/s. Slight reduction of the difference of water volume run-off between seasons for this period ($RSWV_1 = 3.04$ and $RSWV_2 = 2.61$) is noticed when compared to the previous one.

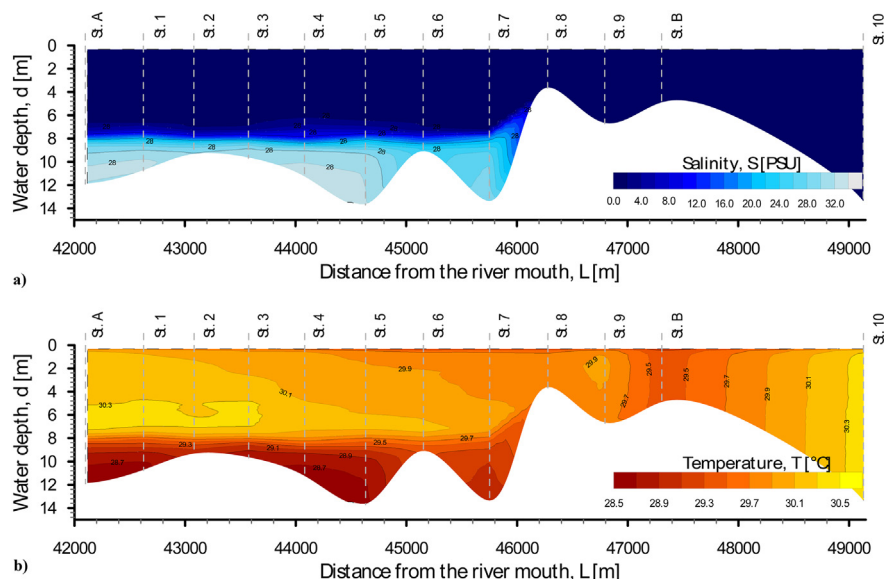


Fig. 5. Longitudinal distribution of a) salinity and b) temperature on June 5th.

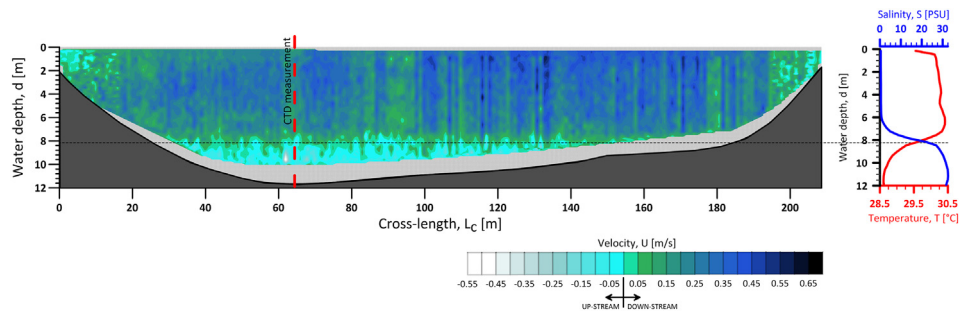


Fig. 6. Cross-sectional velocity field of the upper-estuary of the Grijalva River at St. A. Positive velocity magnitudes represents flow directed downstream and negative velocities belongs to the upstream direction. A no-data region in the bottom of the cross-section was obtained as a result of the blanking distance required by the ADCP measurements to provide valid data.

- iii) After the second (1974–1980) and third dam (1980–1987) started their operations, an almost complete loss of hydrological seasonality occurred when compared to 1957–1964 (Fig. 7). The Q_{mean} changed 46.97%, thus representing almost half the discharge. Slight variation of 4.27% of the mean annual discharge (i.e. $121.08 < Q_{\text{mean}} < 126.49 \text{ m}^3/\text{s}$) between both periods (1974–1980 and 1980–1987) was observed (Table 2). The values of $\text{RSVW}_1 = 1.10$ – 1.20 and $\text{RSVW}_2 = 1.02$ – 1.34 in this period indicate a considerable and severe decrease in the seasonality (Table 2).
- iv) During 1987–2014, with the four-dam system fully operating, the water volume in the rainy season was only 1.30 times more than during the dry season. This results 2.43 times lower than the original difference (RSVW_1) observed in 1957–1964. However, the average annual discharge increased from $Q_{\text{mean}} = 126.49$ (1980–1987) to $Q_{\text{mean}} = 252.65 \text{ m}^3/\text{s}$ (1987–2014).

Comparison of daily water volumes before dam construction and current conditions is considered through the difference between the hydrograph from Period 5 and that from Period 1. By assuming the water volume before the dams as a baseline, the accumulated excess/decrease of water volume for each season is given by the area below the current water volume scenario (Fig. 8). For the dry season, an accumulated water volume excess of 8.914 hm^3 was obtained, while a reduction of 8.596 hm^3 and of 1.939 hm^3 were found for the rainy and Nortes season, respectively, making evident the hydrological changes.

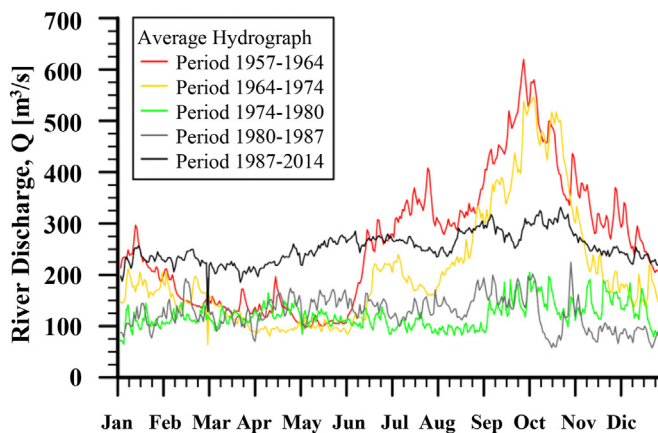


Fig. 7. Average hydrographs during the periods before dams were constructed (1957–1964), after the starting operation of the first dam (1964–1974), second (1974–1980), third (1980–1987) and fourth dam (1987–2014) within the Grijalva River.

3.3. Land use changes

Changes in land use and cover, along with the hydrological regime modifications, could be appreciated over different periods after 1982 (Fig. 9 and Table 3). Among the most relevant changes are the following:

- An annual average rate of $68 \text{ km}^2/\text{yr}$ of cultivated grasslands, introduced as a consequence of agriculture and governmental policies are the major land use change introduced within the area during 1982–1997, increasing from 2870.09 to 3890.20 km^2 .
- The amount of induced grassland, possibly related to the elimination of the original vegetation and from abandoned agricultural areas, fell substantially after 1982, with a reduction of 98.7% between 1982 and 1997 and almost 99.5% between 1982 and 2013. This reduction is associated with the land use providing cultivated grasslands. Also, induced grasslands were mainly found to replace riparian vegetation from the river channels on the west portion of the BRPC and upstream, up to the tular vegetation limit.
- About 223.48 km^2 of mangrove systems were lost between 1982 and 1997, nearly 17.2% of the initial coverage. Mangrove locations close to the mouth of the Grijalva River and the east coastline were occupied by extensive areas of cultivated grassland. However, from 1997 to 2013, the area of mangrove and cultivated grassland remained similar.
- Significant reduction in tular (herbaceous rooted vegetation in shallow water bodies) of about 1346 km^2 (29.7% of the original coverage) occurred in the lowlands 1982–1997. This reduction continued for the years following, representing 140 km^2 , 1997–2013. The area covered by tular was replaced by cultivated grassland and popal (emerging herbaceous vegetation in freshwater wetlands). These changes are observed close to river channels at the western limit of the Biosphere Reserve “Pantanos de Centla” (BRPC).
- The popal vegetation cover was not originally registered in 1982; however, there was an increase on it of 118 km^2 in 1997–2003 (i.e. about 17.0%). Popal vegetation was first noticed in 1997 close to the study area. In 2003 and 2013, slight variations in the popal cover were observed.
- The extension of the savannah, mainly grass with trees spread over poorly-drained land and subject to periodic fires, fell from 73.04 to 5.94 km^2 . An overall reduction of 91.9% between 1982 and 2013 was observed, of which 69.4% belongs to 1982–1997.
- The expansion of the lowland semi-evergreen rainforest occurred within the Protected Area of Fauna and Flora “Laguna de Términos” (APFFLT) when comparing 1982, 1997 and 2003, but between 2003 and 2013 reduction of this forest type was quite significant. Also, the increase of the highland evergreen rainforest was seen in the south of the APFFLT.

In the upper estuary of the Grijalva River, in the Biosphere Reserve “Pantanos de Centla” (BRPC), land use changes show that cultivated

Table 2

Mean, maximum and minimum river discharges and water volumes during dry/rainy seasons and at the different periods of the dam-system functioning.

Period	Q_{mean} [m ³ /s]	Q_{max} [m ³ /s]	Q_{min} [m ³ /s]	Average water volume per year [hm ³] ^{a,b}			Ratio of seasonal water volume, [–]	
				Nortes (V_{NORTES})	Dry season (V_{DRY})	Rainy season (V_{RAINY})	RSWV ₁ $V_{\text{RAINY}}/V_{\text{DRY}}$ [–]	RSWV ₂ $V_{\text{NORTES}}/V_{\text{DRY}}$ [–]
1 1957–1964	263.56	619.80	98.71	3167.04	1241.81	3925.55	3.16	2.55
2 1964–1974	207.15	545.38	63.92	2572.76	984.59	2993.12	3.04	2.61
3 1974–1980	121.08	204.24	65.86	1492.91	1110.67	1225.23	1.10	1.34
4 1980–1987	126.49	224.86	57.58	1263.64	1241.63	1494.63	1.20	1.02
5 1987–2014	252.65	331.39	128.53	2913.44	2202.73	2873.22	1.30	1.32
Differences between period 1 & 5	10.91	288.41	–29.82	253.6	–960.92	1052.33	1.86	1.23

^a 1 hm³ = 1 million of m³.^b The period from March 1st–June 15th was considered for the calculation of water volume during the dry season. The rainy and Nortes season considered 16th June–15th October and 16th October–28th February, respectively.

grasslands increased 2.31 times during 1982–1997 (from 228.23 to 832.95 km²), before and after the area was declared a reserve (1992). This is a high conversion rate when compared to the whole area of the lowlands of the Grijalva-Usumacinta Basin for the same period (Table 3). The cultivated grasslands increased along the upper estuary of the Grijalva River, upstream of the river mouth, in the west of the BRPC and along the Usumacinta River and its effluents. For the same period, reductions of tular and mangrove vegetation of about 627.2 and 63.13 km², respectively, occurred. The reduction of the tular was observed in the southwest of the BRPC, close to the upper estuary of the Grijalva River, in the east and southeast of the BRPC and on the Usumacinta River. The reduction in mangrove occurred along the Grijalva River, being substituted by popal and cultivated grasslands, in the west of the BRPC.

Five years after the area was declared a Reserve and until 2013, cultivated grasslands continued to increase reaching 76.91 km² (~4.8 km²/yr). Instead, reduction in mangrove, rainfed crops, and riparian rainforest constituted about 28.9, 8.8 and 1.6 km², respectively. The reduction of mangrove was noticed on the Grijalva estuary and the west part of the BRPC. In the upper estuary of the Grijalva River, popal vegetation was reduced, substituted by cultivated grassland and tular vegetation. Integration of low- and highland evergreen rainforest was noticed in the southeast of the BRPC (Fig. 10).

4. Discussion

The field measurements from the upper estuary of the Grijalva River reflect the balance between the exchange of salt- and freshwater in the estuary through retreats of the saline intrusion during the rainy and Nortes seasons. The advance of the saline intrusion during the dry season reached 46 km length upstream the river mouth, with values up

to 32.8 PSU. Characteristic features of water temperature and salinity, also described by density changes in relation with water depth, were identified. Freshwater flows and the salt-wedge showed a density of $\rho \approx 992$ kg/m³ and $\rho \approx 1020$ kg/m³, respectively. The halocline and thermocline were located at $d = 8.3$ and 8.5 m, respectively. The development of a morphological bottom change (at the convergence of the Grijalva and Chilapa rivers in St. B) and well-defined modifications on water features (as observed in St. A) were noticed. This demonstrates a delimitation between the estuarine environment and the wetlands upriver, which is related to the current hydrological regime in the basin.

Modifications in the water discharge since the 1950s, due to the construction of the four-dam system on the Grijalva River, outline the implications over saline intrusion and the ecosystems in the surrounding area. The Grijalva River hydrographs (1987–2014) show the critical shift from the original state of conservation of the estuary and the threat to seasonality, as a function of the substantially modified freshwater inflow and excess/decrease of seasonal water volumes between dry, rainy and Nortes seasons. The ratio of the total volume availability of freshwater decreased considerably, from $RSWV_1 = 3.16$ to 1.30 and $RSWV_2 = 2.55$ to 1.32 . These results show that the original salt intrusion could have reached different limits and ecological influence, upstream and downstream, as a balance between the modified freshwater discharge and tidal forcing (Geyer and Farmer, 1989). Despite this seasonality threat, the salt-wedge still exists, a sign of the system's resilience. However, research on coastal forcings and further processes (e.g. tides, waves, and energy flux) is required to further understand the mechanisms of this resilience related to the modified freshwater discharge in the estuarine dynamics as well as on sediment transport altered by the dam system and for which monitoring is necessary.

Additionally, the most relevant land use changes were observed during 1982–1997, a period characterized by the last, severe modifications in the hydrological regime. After this period, the hydrological regime stabilized (Fig. 2) and the rate of land use changes decreased (Table 3). However, federal and state agricultural and livestock management policies implemented in 1994–2000, with \$ 11,354,875 USD investment and occupying approx. 1800 km² by 2015 (De la Rosa-Velázquez et al., 2017), possibly led to modifications in the tropical estuarine environment. The change from natural vegetation cover (i.e. mangrove, tular, savannah, palmar) in the lowlands of the Grijalva River, to cultivated grassland, rainfed agriculture, popal and urban areas are some of the most visible impacts, with >2000 km². Cultivated grasslands represent >67.3% of these changes, mostly driven by the economic policies during the 1950's in the river basin. Further modifications include the loss of 1486 km² of the tular vegetation, mainly replaced in its periphery by popal and lowland evergreen rainforest. This could possibly relate to successional stages of vegetation, the degree of potential fragmentation and threaten the environment (Kemp et al., 2016; Thom Bruce, 1967; Tudela, 1992). These results are closely related to the principles of the hydraulic plans and their development stages in the area (Tudela, 1992): a) exploitation of low-affected

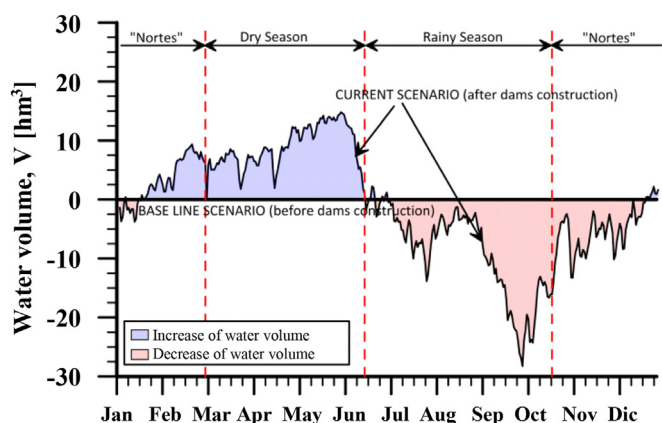


Fig. 8. Water volume changes between the natural condition (baseline scenario, i.e. zero-line) and the current conditions after the four-dam system operation.

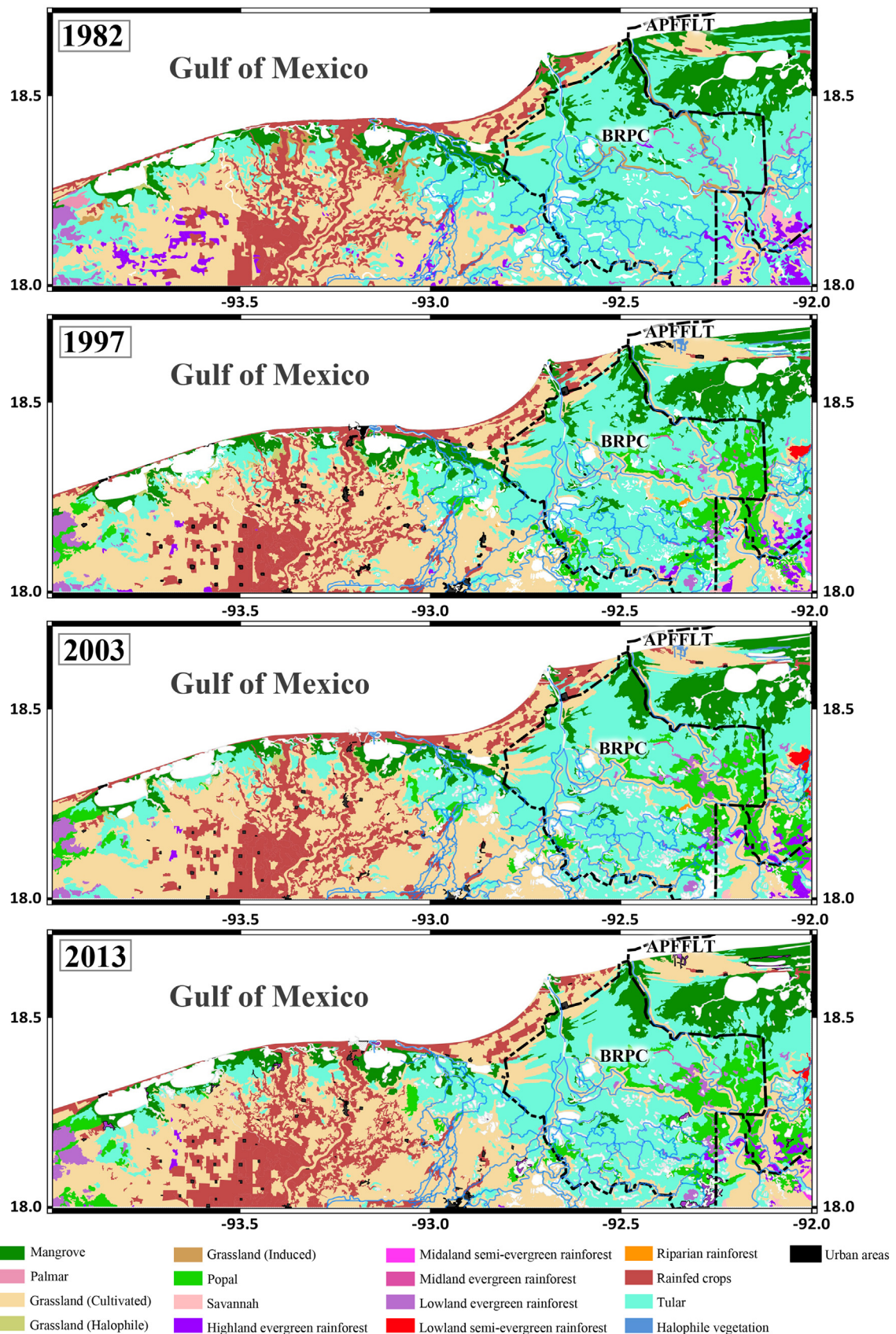


Fig. 9. Vegetation cover and land use distribution for the periods 1982, 1997, 2003, 2013.

Table 3

Vegetation and land use, areas and rate of changes for the periods 1982, 1997, 2003 and 2013 for the lowlands of the Grijalva-Usumacinta basin.

Vegetation and land use	Area* [km ²]				Rate of change* [%]		
	1982	1997	2003	2013	(1982–1997)	(1997–2003)	(2003–2013)
Lowlands of the Grijalva-Usumacinta basin							
Mangrove	1297.69	1074.21	1083.85	1093.75	−17.2%	0.9%	0.9%
Palmar	23.37	4.15	1.56	1.90	−82.2%	−62.4%	22.2%
Grassland (cultivated)	2870.09	3890.20	3874.15	3842.49	35.5%	−0.4%	−0.8%
Grassland (halophile)	9.12	42.61	35.19	18.05	367.3%	−17.4%	−48.7%
Grassland (induced)	223.82	2.82	2.29	1.08	−98.7%	−18.8%	−53.0%
Popal	NA	696.58	814.84	789.54	–	17.0%	−3.1%
Savannah	73.04	22.31	8.62	5.94	−69.4%	−61.4%	−31.1%
Highland evergreen rainforest	303.66	105.71	90.28	77.00	−65.2%	−14.6%	−14.7%
Midland semi-evergreen rainforest	–	16.72	6.89	5.70	–	−58.8%	−17.4%
Midland evergreen rainforest	3.61	2.85	2.85	2.85	−20.9%	0.0%	0.0%
Lowland evergreen rainforest	173.07	175.56	184.35	201.60	1.4%	5.0%	9.4%
Lowland semi-evergreen rainforest	–	17.49	29.30	12.99	–	67.6%	−55.7%
Riparian rainforest	–	8.18	4.28	4.28	–	−47.7%	0.0%
Rainfed crops	1229.88	1281.14	1294.20	1444.88	4.2%	1.0%	11.6%
Tular	4534.38	3188.43	3108.20	3048.35	−29.7%	−2.5%	−1.9%
Halophile vegetation	–	29.02	26.00	25.45	–	−10.4%	−2.1%
Urban areas	–	57.41	59.85	64.74	–	4.2%	8.2%
Biosphere Reserve “Pantanos de Centla” (BRPC) ^a							
Mangrove	421.27	358.13	357.63	329.19	−15.0%	−0.1%	−8.0%
Grassland (cultivated)	228.23	756.04	804.58	832.95	231.3%	6.4%	3.5%
Grassland (induced)	53.25	0.00	0.00	0.00	−100.0%	–	–
Popal	NA	291.02	302.90	295.85	–	4.1%	−2.3%
Savannah	3.83	3.96	0.00	0.00	3.5%	−100.0%	–
Highland evergreen rainforest	8.59	8.23	2.13	3.29	−4.2%	−74.1%	54.6%
Midland evergreen rainforest	2.02	1.60	1.60	1.60	−20.9%	0.0%	0.0%
Lowland evergreen rainforest	22.73	39.97	47.58	46.00	75.8%	19.1%	−3.3%
Riparian rainforest	–	3.98	2.40	2.40	–	−39.8%	0.0%
Rainfed crops	9.21	13.11	12.00	4.33	42.4%	−8.5%	−63.9%
Tular	1914.36	1287.16	1314.10	1358.75	−32.8%	2.1%	3.4%
Urban areas	–	2.28	2.05	2.05	–	−10.2%	0.0%

^a The BRPC was declared on 1992, no previous protection is identified before this date.

inundation areas (before dams); b) utilization of new lowlands after flood regulation by the first dams (not used for water storage); and c) full operation of the dam system and homogeneity of the hydrological regime (Fig. 7 and Table 2).

Although further land use changes were limited by the declaration of the BRPC in 1992, the expansion of cultivated grasslands continued, as well as its pressure in the estuarine environment, on the river banks and in the surrounding area. Environmental conservation strategies, management plans, and policies were implemented to protect the Grijalva River lowlands and its upper estuary (DOF, 1997; UNESCO, 2012), recently modified through the “Law for environmental protection of the state of Tabasco”, “Law for water use of the State of Tabasco”, “Forestry law of the state of Tabasco”, “Law of Sustainable Management of the Territory of the State of Tabasco” policies (DOF, 2017a, b, c, d). However, these policies are for the conservation and protection of a highly-perturbed estuarine environment, as substantial changes (1959–1987) were already developed in the hydrological regime, land use, and vegetation cover. The interaction between the coastal plains and upstream conditions for the estuarine environment seems to be neglected, as shown by the definition of the limits of the Biosphere Reserve “Pantanos de Centla”. In fact, this definition did not consider the interaction of the estuarine system either with the coastal plains or with the upstream conditions beyond the reserve limit.

Strategies and techniques for watershed management require field measurements and analytical methods to assess the cumulative impacts of the dams. However, they are normally not considered for the large extension of ecosystems and their connectivity, but represent a primary component of river management (Zhou et al., 2017). Therefore, detailed analysis and the assessment of water quality properties, nutrients (e.g. nitrate + nitrite, silicate), suspended particulate matter (SPM) and phytoplankton biomass (chlorophyll *a*) (e.g. Damar, 2012; Haraguchi et al., 2015; Laino-Guanes et al., 2016) are needed. This might allow linkage of river management and estuarine wetland conservation, as they are

crucial to understand the full dynamics of the estuarine ecosystem and the effects of natural/human stressors.

5. Conclusions

Seasonal variability of salinity, temperature, water-discharge and flow velocities were presented for the tropical upper estuary of the Grijalva River, in the southern Gulf of Mexico. Monthly field measurements were provided for the characterization of the salt-wedge: i) freshwater flows of 0–1.0 PSU; ii) salt-wedge with 20–32.76 PSU with the halocline at 8.26 m depth; and iii) development of salt-intrusion, 46 km upstream from the river mouth. These conditions could be related to the current hydrological regime as part of the balance and interaction in the estuary of freshwater discharge and marine processes. The decrease in river discharge during Nortes and rainy seasons shows an almost complete loss of the hydrological seasonality, substantially modified since 1959, due to the dam system. The advance inland of the salt-wedge tongue was found to be limited by a submerged morphological obstacle, which possibly acts as a natural boundary between the estuary and upstream environments, in addition to the salinity-temperature conditions.

The increase in extension of cultivated grassland (>1020 km²) in the Grijalva River lowlands (1982–2013) and in the BRPC (before 1992), is a relevant stress factor for the estuarine environment. Although modifications were less in the BRPC, due to conservation policies, pressure and stressors were identified at the boundaries caused by land use changes and possibly by successive stages of vegetation. The estuarine environment, even after the protected area was designated as such, had already been altered as part of the expected interaction between environments within the protected and surrounding areas (i.e. due to the estuary dependency on changes upriver and in adjacent coastal zones).

Implementation of the large water regulation management plan (imposed by the four-dam system since 1959, along with changes in

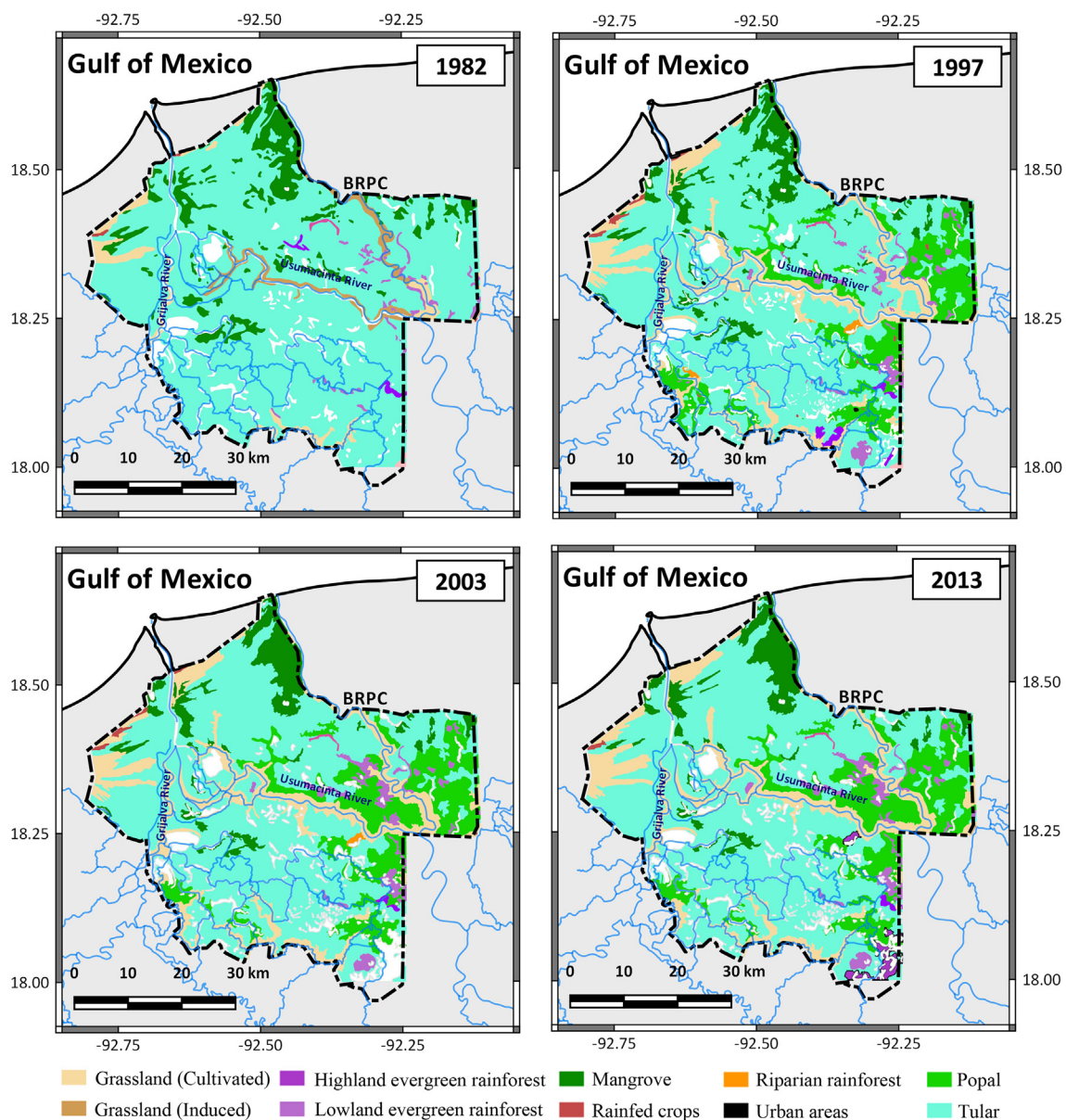


Fig. 10. Land use changes at the Biosphere Reserve "Pantanos de Centla".

land use policies in the Grijalva basin), have had a series of cumulative effects over the estuarine environment and the development of the adjacent areas. Understanding the physical processes and the effects of saline intrusion on estuarine environments and adaptation/relation to natural and anthropic perturbations are fundamental for long-term development. Dam planning in the tropics normally lacks the consideration of ecosystem services and biodiversity conservation, but instead is based on a scheme of benefits which do not necessarily enhance the quality of life or full economic growth in the existing and currently prevailing rural communities in these systems (Winemiller et al., 2016). Natural and artificial changes, as well as their long-term impacts (e.g. effects of agro-pesticides, water and soil salinization, nutrient transport), should also be considered. Therefore, research is crucial for adaptive co-management in estuarine and coastal zones. Work is still needed to explain the integrated analysis from continuous monitoring of physical, chemical, biological and ecological processes. This characterization might allow overcoming the non-fully recognized hydrological response, processes of environmental fragmentation and effects of anthropic stressors. Climate change scenarios should be drawn, as

saltwater intrusion is expected to worsen in low-lying coastal areas around the world and which sums to the increasing hydropower dam construction developments for the 21st century.

Acknowledgements

The authors acknowledge CONACYT (Project 247119) for the development of the present study as well as to Aarón Jarquín, Arturo Álvarez and Jorge Suárez for their support to the fieldwork conducted and Martha Huerta for her assistance on the graphical abstract.

References

- Anh Duc, N., 2008. Salt Intrusion, Tides and Mixing in Multi-channel Estuaries. Taylor & Francis/Balkema, Delt, The Netherlands.
- Barba-Macías, E., Rangel-Mendoza, J., Ramos-Reyes, R., 2006. Clasificación de los humedales de Tabasco mediante sistemas de información geográfica. Univ. Cienc. 22, 11.
- Bates, B.C., Kundzewicz, Z.W., Wu, S., Palutikof, J.P., 2008. Climate Change and Water, Climate Change and Water. Technical Paper of the Intergovernmental Panel on Climate Change. IPCC, Geneva.

- Bricheno, L.M., Wolf, J., Islam, S., 2016. Tidal intrusion within a mega delta: an unstructured grid modelling approach. *Estuar. Coast. Shelf Sci.* 182, 12–26. <https://doi.org/10.1016/j.ecss.2016.09.014>.
- CFE, 2016. Informe Anual 2015-Comisión Federal de Electricidad (CFE) (Mexico).
- Chua, V.P., Xu, M., 2014. Impacts of sea-level rise on estuarine circulation: an idealized estuary and San Francisco Bay. *J. Mar. Syst.* 139, 58–67. <https://doi.org/10.1016/j.jmarsys.2014.05.012>.
- CONAGUA, 2016. Estadísticas del agua en México. 2016th ed. Secretaría del Medio Ambiente y Recursos Naturales-Comisión Nacional del Agua (SEMARNAT-CONAGUA), Mexico.
- CONAGUA, 2018. Banco Nacional de Datos de Aguas Superficiales (BANDAS) (Mexico).
- Damar, A., 2012. Net phytoplankton community structure and its biomass dynamics in the Brantas River Estuary, Java, Indonesia. *Coastal Environments: Focus on Asian Regions*. Springer Netherlands, Dordrecht, pp. 173–189 https://doi.org/10.1007/978-90-481-3002-3_12.
- De la Rosa-Velázquez, M.J., Espinoza-Tenorio, A., Díaz-Perera, M.A., Ortega-Argueta, A., Ramos-Reyes, R., Espejel, I., 2017. Development stressors are stronger than protected area management: a case of the Pantanos de Centla Biosphere Reserve, Mexico. *Land Use Policy* 67, 340–351. <https://doi.org/10.1016/j.landusepol.2017.06.009>.
- DOF, 1997. Programa de manejo del Área de Protección de Flora y Fauna “Laguna de Términos”. 11. D. Of. la Fed.
- DOF, 2017a. Ley de protección ambiental del estado de Tabasco [Law of environmental protection of the State of Tabasco] (Mexico).
- DOF, 2017b. Ley de uso de agua del estado de Tabasco [Law for water use for the state of Tabasco] (Mexico).
- DOF, 2017c. Ley forestal del Estado de Tabasco [Forestry law of the state of Tabasco] (Mexico).
- DOF, 2017d. Ley de ordenamiento sustentable del territorio del estado de Tabasco [Law of sustainable management of the territory of the State of Tabasco] (Mexico).
- Eyre, B., Balls, P., 1999. A comparative study of nutrient behavior along the salinity gradient of tropical and temperate estuaries. *Estuaries* 22, 313. <https://doi.org/10.2307/1352987>.
- Feng, Y., Sun, T., Zhu, M.S., Qi, M., Yang, W., Shao, D.D., 2017. Salt marsh vegetation distribution patterns along groundwater table and salinity gradients in yellow river estuary under the influence of land reclamation. *Ecol. Indic.* <https://doi.org/10.1016/j.ecolind.2017.09.027>.
- Franco Maass, S., Regil García, H.H., González Esquivel, C., Nava Bernal, G., 2006. Cambio de uso del suelo y vegetación en el Parque Nacional Nevado de Toluca, México, en el periodo 1972–2000. *Investig. Geográficas*, pp. 38–57.
- García García, A., Kauffner Michel, E.F., 2011. Las cuencas compartidas entre México, Guatemala y Belice: Un acercamiento a su delimitación y problemática general. (*Front. Norte*). 23 pp. 131–161.
- Geyer, W.R., Farmer, D.M., 1989. Tide-induced variation of the dynamics of a salt wedge estuary. *J. Phys. Oceanogr.* [https://doi.org/10.1175/1520-0485\(1989\)019<1060:TIVOTD>2.0.CO;2](https://doi.org/10.1175/1520-0485(1989)019<1060:TIVOTD>2.0.CO;2).
- Gong, W., Shen, J., 2011. The response of salt intrusion to changes in river discharge and tidal mixing during the dry season in the Modaomen Estuary, China. *Cont. Shelf Res.* 31, 769–788. <https://doi.org/10.1016/j.csr.2011.01.011>.
- Gong, W., Wang, Y., Jia, J., 2012. The effect of interacting downstream branches on saltwater intrusion in the Modaomen Estuary, China. *J. Asia Earth Sci.* 45, 223–238. <https://doi.org/10.1016/j.jseas.2011.11.001>.
- Gong, W., Shen, J., Jia, L., 2013. Salt intrusion during the dry season in the Huangmaohai Estuary, Pearl River Delta, China. *J. Mar. Syst.* 111–112, 235–252. <https://doi.org/10.1016/j.jmarsys.2012.11.006>.
- Haraguchi, L., Carstensen, J., Abreu, P.C., Odebrecht, C., 2015. Long-term changes of the phytoplankton community and biomass in the subtropical shallow Patos Lagoon Estuary, Brazil. *Estuar. Coast. Shelf Sci.* 162, 76–87. <https://doi.org/10.1016/j.ecss.2015.03.007>.
- INECC, 2018. La cuenca de los ríos Grijalva y Usumacinta [WWW Document]. Inst. Nac. Ecol. y Cambio Climático URL. <http://www2.inecc.gob.mx/publicaciones2/libros/402/cuencas.html>, Accessed date: 8 January 2018.
- INEGI, 2018. Conjunto de Datos Vectoriales de Carta de uso del Suelo y Vegetación [escala 1:250000]. Series I, II, III, IV, V.
- Jansson, R., Nilsson, C., Renöfält, B., 2000. Fragmentation of riparian floras in rivers with multiple dams. *Ecology* 81, 899–903. [https://doi.org/10.1890/0012-9658\(2000\)081\[0899:FORFIR\]2.0.CO;2](https://doi.org/10.1890/0012-9658(2000)081[0899:FORFIR]2.0.CO;2).
- Kauffer Michel, E.F., 2010. Migraciones y agua en la frontera entre México, Guatemala y Belice: aproximaciones en torno a una relación multifactorial. *Limnol. Centro de Estudios Superiores de México y Centroamérica de la Universidad de Ciencias y Artes de Chiapas, San Cristóbal de Las Casas, Chiapas, México*.
- Kemp, G.P., Day, J.W., Yañez-Arancibia, A., Peyronnin, N.S., 2016. Can continental shelf river plumes in the northern and southern Gulf of Mexico promote ecological resilience in a time of climate change. *Water* 8, 83.
- Laino-Guanes, R., González-Espinoza, M., Ramírez-Marcial, N., Bello-Mendoza, R., Jiménez, F., Casanoves, F., Musálem-Castillejos, K., 2016. Human pressure on water quality and water yield in the upper Grijalva river basin in the Mexico-Guatemala border. *Ecohydrol. Hydrobiol.* 16, 149–159. <https://doi.org/10.1016/j.ecohyd.2015.12.002>.
- López-Ramírez, A., 2007. Vulnerabilidad y resistencia hidropolíticas en América Central y Las Antillas. In: Wolf, T. (Ed.), *Vulnerabilidad y Resistencia Hidropolíticas en Aguas Internacionales*. América Latina y El Caribe. PNUMA/Universidad Nacional Costa Rica/Oregon State University, p. 152.
- McLusky, D.S., Elliott, M., 2004. *The Estuarine Ecosystem Ecology, Threats and Management*. 3rd ed. Oxford University Press, Oxford, UK.
- Medellín, G., Mariño-Tapia, I., Pedrozo-Acuña, A., Enríquez, C., González-Villarreal, F., 2013. Influencia de la marea en la hidrodinámica del sistema Mecocacán-Río González, México. *Technol. Cienc. Agua* 4, 71–90.
- Nilsson, C., Reidy, C.A., Dynesius, M., Revenga, C., 2005. Fragmentation and Flow Regulation of the World's Large River Systems. *Science* 308, 405–408. <https://doi.org/10.1126/science.1107887> (80–).
- Ortiz-Pérez, M.A., 1992. Retroceso Reciente de la Línea de Costa del Frente Deltaico del Río San Pedro, Campeche-Tabasco. *Investig. Geográficas*, pp. 7–23.
- Prandle, D., Lane, A., 2015. Sensitivity of estuaries to sea level rise: vulnerability indices. *Estuar. Coast. Shelf Sci.* 160, 60–68. <https://doi.org/10.1016/j.ecss.2015.04.001>.
- Psuty, N.P., 1965. Beach-ridge development in tabasco, Mexico. 1. Ann. Assoc. Am. Geogr. 55, 112–124. <https://doi.org/10.1111/j.1467-8306.1965.tb00509.x>.
- Psuty, N.P., 1967. The Geomorphology of Beach-ridges in Tabasco, Mexico. Louisiana State Univ. Press.
- RAMSAR, 2001. RAMSAR sites information service. Reserva de la Biosfera Pantanos de Centla. [WWW document]. URL. rsis.ramsar.org/rsi/733, Accessed date: 1 October 2018.
- Rodríguez, Y., 2010. La Región Usumacinta en México, Segunda Etapa. Características y especificaciones de la agenda común para el desarrollo de la región (No. Code: 143289–2010), Convenio de asignación de recursos que celebran el Fondo Institucional de Fomento Regional para el Desarrollo Científico, Tecnológico y de Innovación (FORDECYT) y el Centro de Investigación en Geografía y Geomática “Ing. Jorge L. Tamayo” AC.
- Sánchez, A.J., Barba-Macias, E., 2005. Biodiversidad de Tabasco. In: Bueno, J., Álvarez, F., Santiago, S. (Eds.), *Biodiversidad Del Estado de Tabasco*. Comisión Nacional para el Conocimiento y Uso de la Biodiversidad, Instituto de Biología-UNAM, Mexico.
- Savenije, H.H.G., 2012. *Salinity and Tides in Alluvial Estuaries*. 2nd ed. Delft University of Technology, Amsterdam, The Netherlands.
- SEMARNAT, 2016. Reserva de la Biosfera Pantanos de Centla, Tabasco [WWW Document]. Secr. Medio Ambient. y Recur. Nat. URL. <https://www.gob.mx/semarnat>.
- Shivaprasad, A., Vinita, J., Revichandran, C., Reny, P.D., Deepak, M.P., Muraleedharan, K.R., Naveen Kumar, K.R., 2013. Seasonal stratification and property distributions in a tropical estuary (Cochin estuary, west coast, India). *Hydrol. Earth Syst. Sci.* 17, 187–199. <https://doi.org/10.5194/hess-17-187-2013>.
- Thom Bruce, G., 1967. Mangrove ecology and deltaic geomorphology: Tabasco, Mexico. *J. Ecol. Br. Ecol. Soc.* 55, 301–343.
- Tudela, F., 1992. La modernización forzada del trópico: El caso de Tabasco, proyecto integrado del Golfo. El Colegio de México, Mexico.
- UNESCO, 2012. Mexico. Pantanos de Centla [WWW Document]. UNESCO-Biosphere Reserv. URL. <http://www.unesco.org/new/en/natural-sciences/environment/ecological-sciences/biosphere-reserves/latin-america-and-the-caribbean/mexico/pantanos-de-centla/>, Accessed date: 11 February 2018.
- Valle Junior, R.F., Varandas, S.G.P., Sanches Fernandes, L.F., Pacheco, F.A.L., 2014a. Environmental land use conflicts: a threat to soil conservation. *Land Use Policy* 41, 172–185. <https://doi.org/10.1016/j.landusepol.2014.05.012>.
- Valle Junior, R.F., Varandas, S.G.P., Sanches Fernandes, L.F., Pacheco, F.A.L., 2014b. Groundwater quality in rural watersheds with environmental land use conflicts. *Sci. Total Environ.* 493, 812–827. <https://doi.org/10.1016/j.scitotenv.2014.06.068>.
- Valle Junior, R.F., Varandas, S.G.P., Pacheco, F.A.L., Pereira, V.R., Santos, C.F., Cortes, R.M.V., Sanches Fernandes, L.F., 2015. Impacts of land use conflicts on riverine ecosystems. *Land Use Policy* 43, 48–62. <https://doi.org/10.1016/j.landusepol.2014.10.015>.
- Wang, Z.B., Van Maren, D.S., Ding, P.X., Yang, S.L., Van Prooijen, B.C., De Vet, P.L.M., Winterwerp, J.C., De Vriend, H.J., Stive, M.J.F., He, Q., 2015. Human impacts on morphodynamic thresholds in estuarine systems. *Cont. Shelf Res.* 111, 174–183. <https://doi.org/10.1016/j.csr.2015.08.009>.
- Winemiller, K.O., McIntyre, P.B., Castello, L., Fluet-Chouinard, E., Giarrizzo, T., Nam, S., Baird, I.G., Darwall, W., Lujan, N.K., Harrison, I., Stiassny, M.L.J., Silvano, R.A.M., Fitzgerald, D.B., Pelicice, F.M., Agostinho, A.A., Gomes, L.C., Albert, J.S., Baran, E., Petrere, M., Zarfl, C., Mulligan, M., Sullivan, J.P., Arantes, C.C., Sousa, L.M., Koning, A.A., Hoehninghaus, D.J., Sabaj, M., Lundberg, J.G., Armbruster, J., Thieme, M.L., Petry, P., Zuanon, J., Torrente Vilara, G., Snoeks, J., Ou, C., Rainboth, W., Pavanelli, C.S., Akama, A., Van Soesbergen, A., Sáenz, L., 2016. Balancing hydropower and biodiversity in the Amazon, Congo, and Mekong. *Science* 351, 128–129. <https://doi.org/10.1126/science.aac7082> (80–).
- Wolanski, E., Elliott, M., 2016. *Estuarine Ecohydrology: An Introduction*. 2nd ed. Elsevier B.V., Amsterdam, The Netherlands.
- World Energy Council, 2016. *World Energy Resources: Hydropower-2016*.
- Yang, Z., Wang, T., Voisin, N., Copping, A., 2015. Estuarine response to river flow and sea-level rise under future climate change and human development. *Estuar. Coast. Shelf Sci.* 156, 19–30. <https://doi.org/10.1016/j.ecss.2014.08.015>.
- Zarfl, C., Lumsdon, A.E., Berlekamp, J., Tydecks, L., Tockner, K., 2015. A global boom in hydropower dam construction. *Aquat. Sci.* 77, 161–170. <https://doi.org/10.1007/s00027-014-0377-0>.
- Zhou, R., Li, Y., Wu, J., Gao, M., Wu, X., Bi, X., 2017. Need to link river management with estuarine wetland conservation: a case study in the Yellow River Delta, China. *Ocean Coast. Manag.* 146, 43–49. <https://doi.org/10.1016/j.ocecoaman.2017.06.004>.